
Vector Diffraction Simulation for EUV Mask Illuminated by Focused Waves

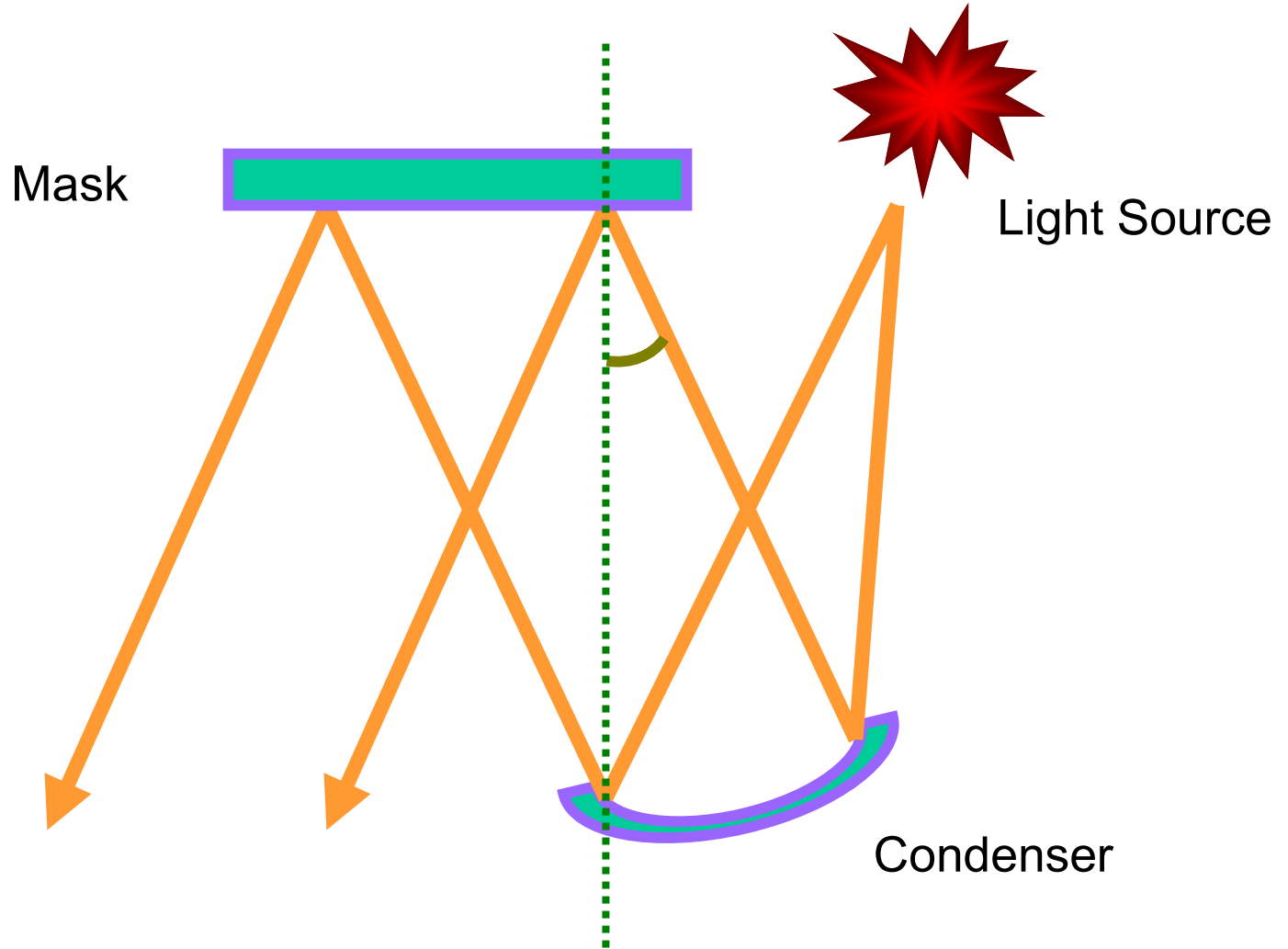
- Optical Properties of EUV Mask in Obliquely Incident Illumination Condition

Mask #33

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Oblique Incidence in EUVL System



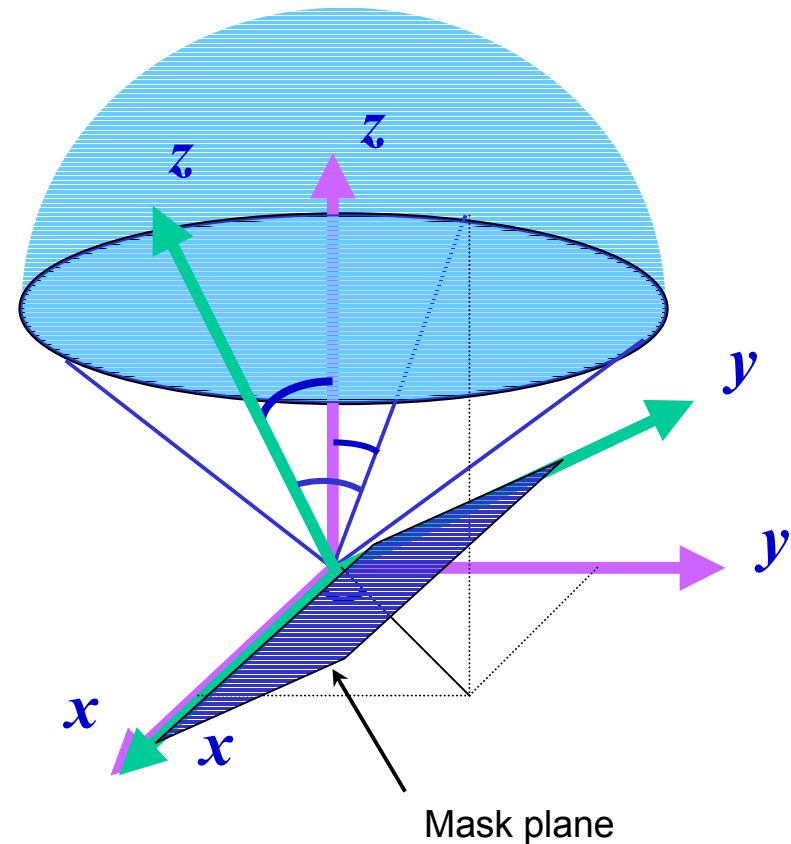
Transformation Matrix for Tilted Coordinate System

Wave vector in the coordinate system (x, y, z) :

$$[k_i] = \begin{pmatrix} k \sin \theta \cos \phi \\ k \sin \theta \sin \phi \\ k \cos \theta \end{pmatrix}$$

Transformation matrix :

$$[A_{ij}] = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \psi & \sin \psi \\ 0 & -\sin \psi & \cos \psi \end{pmatrix}$$



Incident Angle of Illumination Waves in the Tilted Coordinate System

Wave vector in the coordinate system (x, y, z) :

$$[k'_i] = [A_{ij}][k_j] = \begin{pmatrix} k \sin \theta \cos \phi \\ k(\cos \psi \sin \theta \sin \phi + \sin \psi \cos \theta) \\ k(-\sin \psi \sin \theta \sin \phi + \cos \psi \cos \theta) \end{pmatrix}$$

$$\begin{aligned} \hat{z}' \cdot \vec{k}' &= k(-\sin \psi \sin \theta \sin \phi + \cos \psi \cos \theta) \\ &= k \cos \theta' \end{aligned}$$



Incident angle in the the coordinate system (x, y, z) :

$$\theta' = \cos^{-1}(-\sin \psi \sin \theta \sin \phi + \cos \psi \cos \theta)$$

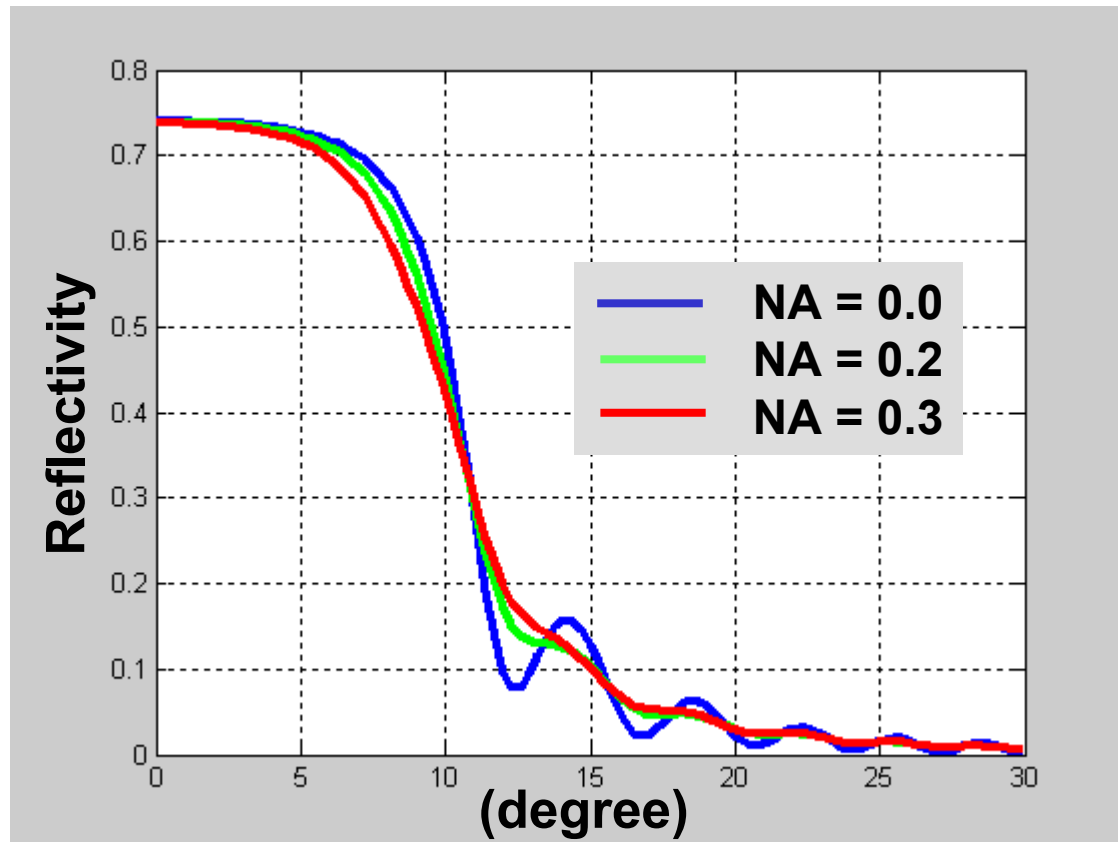
Assumptions and Conditions of Simulation

- Incident angle is determined by

$$\theta' = \cos^{-1}(-\sin \psi \sin \theta \sin \phi + \cos \psi \cos \theta)$$

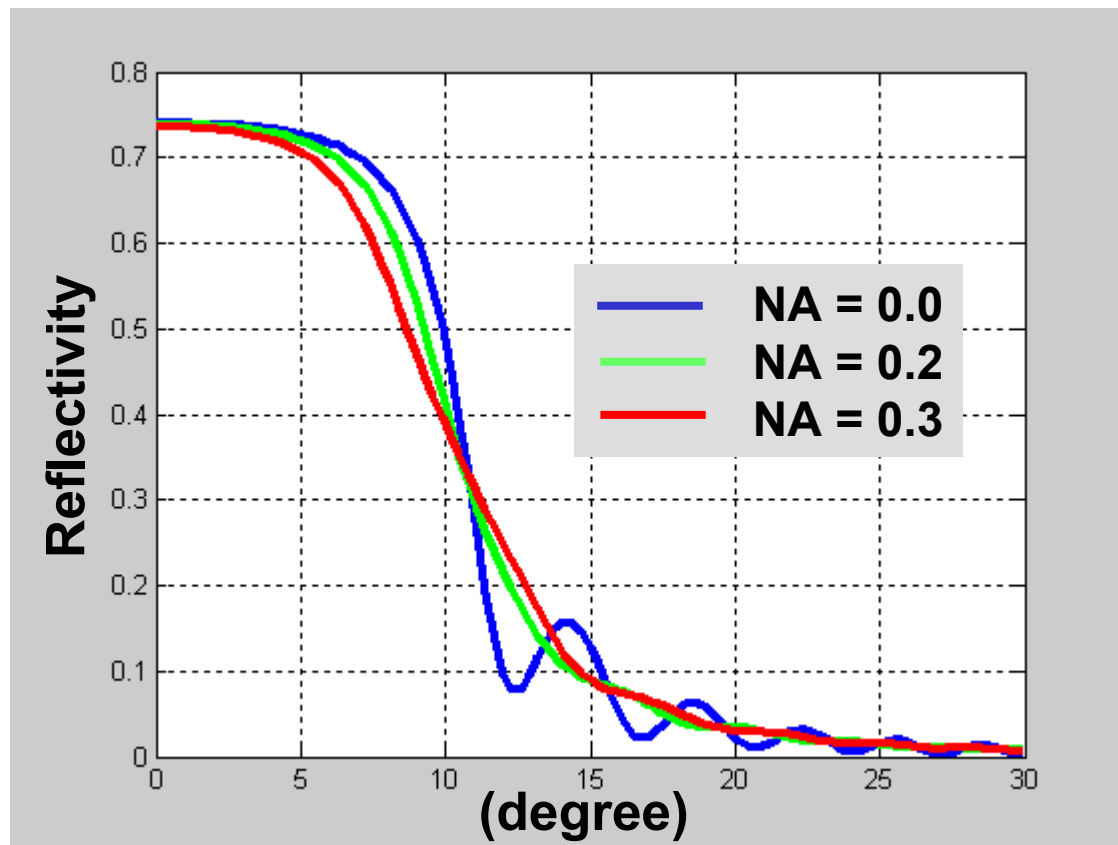
- Illumination beam is unpolarized.
- 40 pairs of Mo/Si multilayer and one single Si layer are deposited on glass substrate.
- 4X of magnification factor is assumed.
- Characteristic Matrix method is used in calculating the reflectivity of layered structure.

Reflectivity vs θ with $n = 1.0$



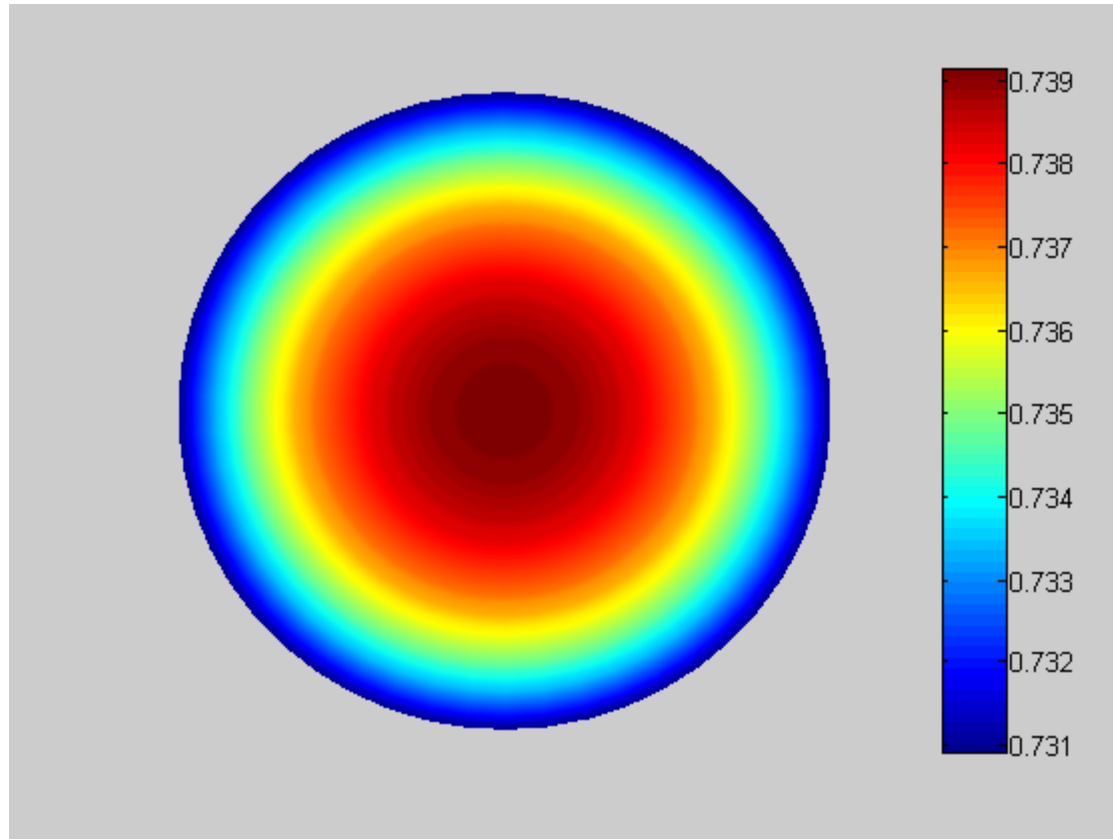
- Thickness of Mo/Si = 2.8 nm/4.1 nm.
- Reflectivity starts to decrease significantly when $\theta = 5^\circ$.
- Reflectivity is sensitive to incident angle because of the extremely strong interference effects induced by Mo/Si multilayer structure.

Reflectivity vs θ with $\text{NA} = 0.5 \sim 1.0$



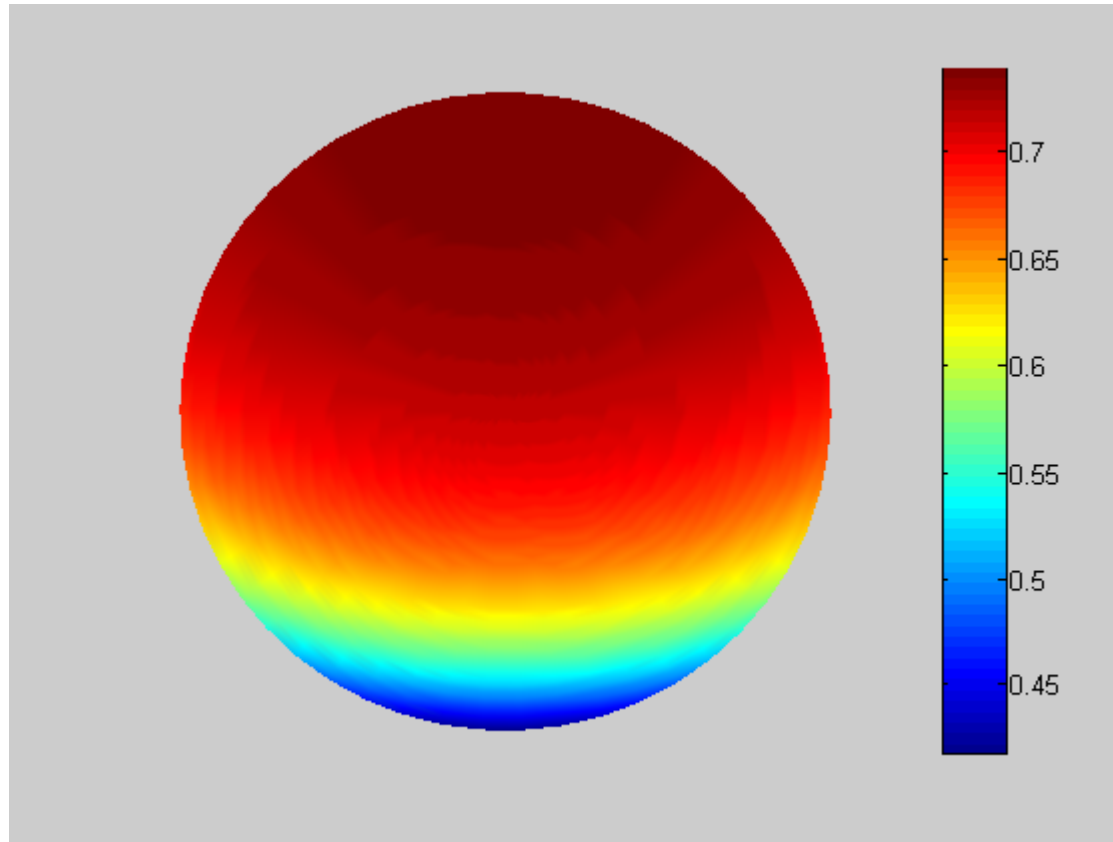
- Thickness of Mo/Si = 2.8 nm/4.1 nm.
- Reflectivity is reduced a little more rapidly in annular illumination condition than in conventional one as NA increases.

Reflectivity Distribution Illustrated over Illumination Aperture for $NA = 0.3$ and $\theta = 0$



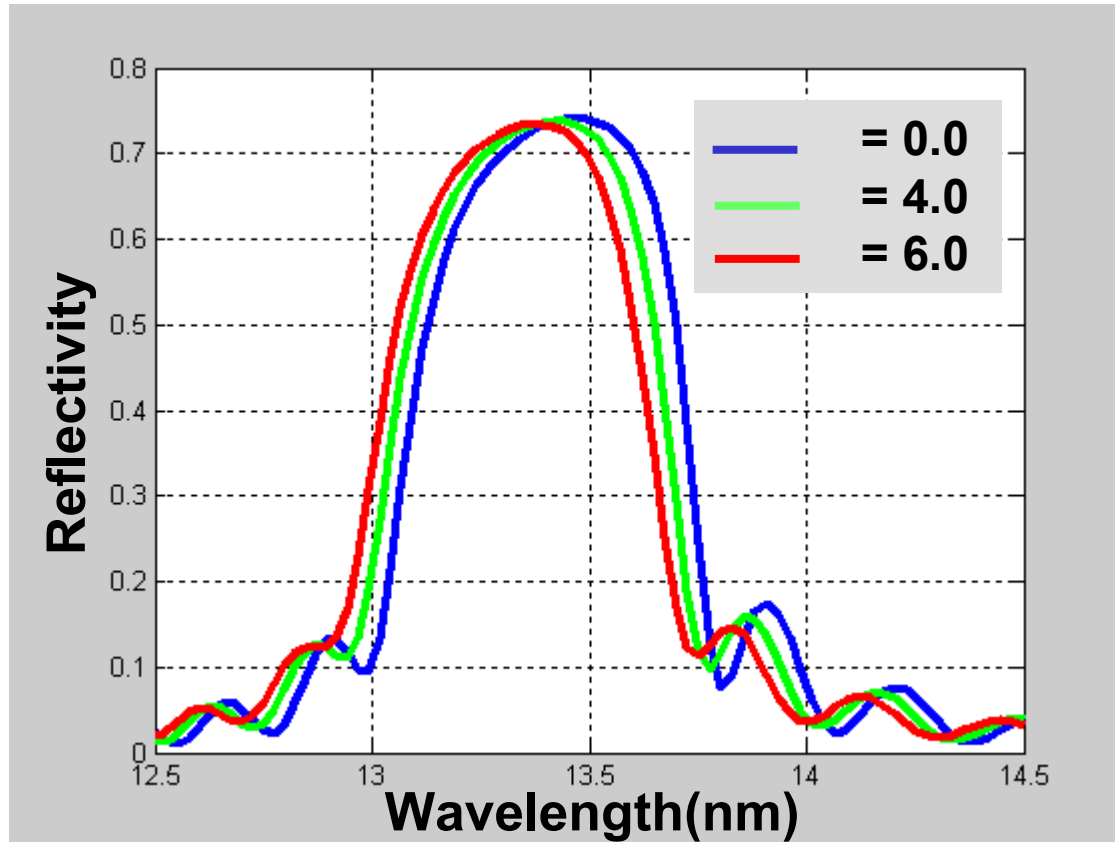
- Reflectivity decreases monotonically as the distance from the center of illumination aperture increases when $\theta = 0$.

Reflectivity Distribution Illustrated over Illumination Aperture for NA = 0.3 and $\theta = 6^\circ$



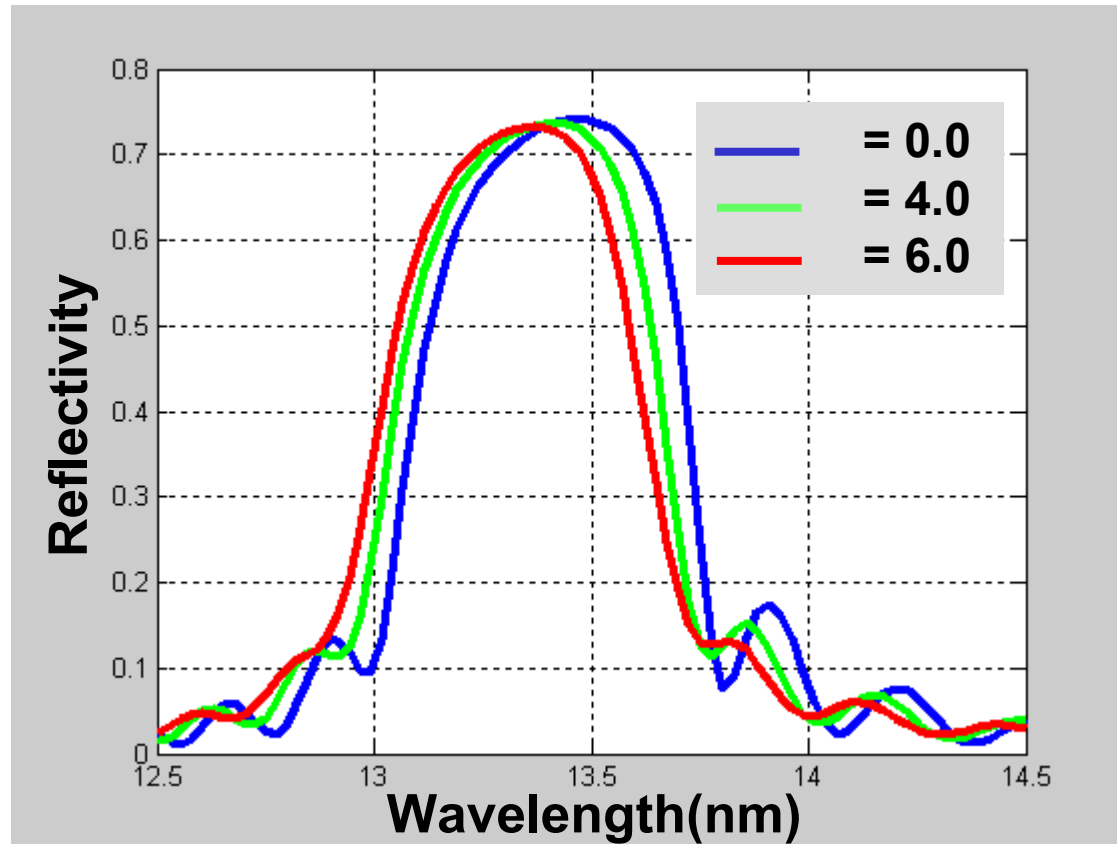
- Reflectivity distribution over illumination aperture is asymmetrical when $\theta \neq 0$, due to the incident angle dependence of reflectivity.
- Reflectivity varies from 0.43 to 0.73 over the illumination aperture.

Reflectivity vs Wavelength for $\lambda = 0, 4, 6$ with NA = 0.3 and $\theta = 1.0$



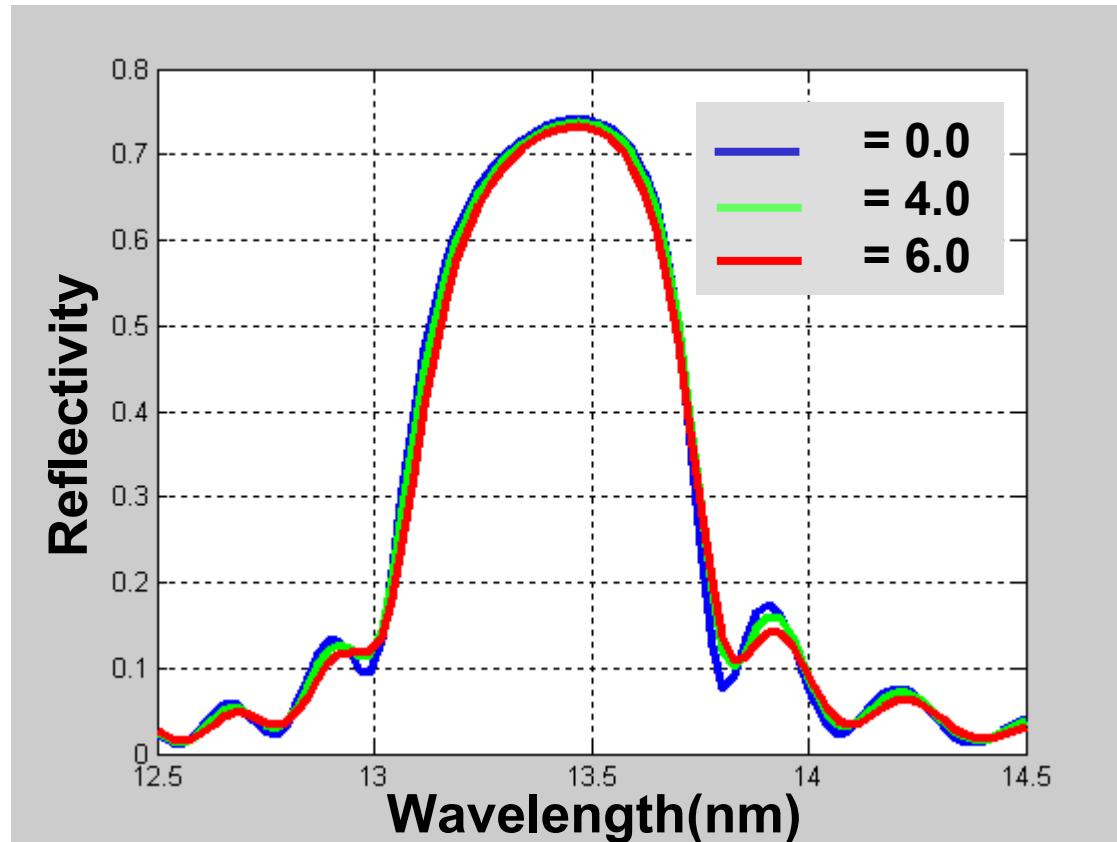
- Thickness of Mo/Si = 2.8 nm/4.1 nm.
- Wavelength of maximum reflectivity shifts to the shorter wavelength side as λ increases.

Reflectivity vs Wavelength for $\lambda = 0, 4, 6$ with NA = 0.3 and $\sigma = 0.5 \sim 1.0$



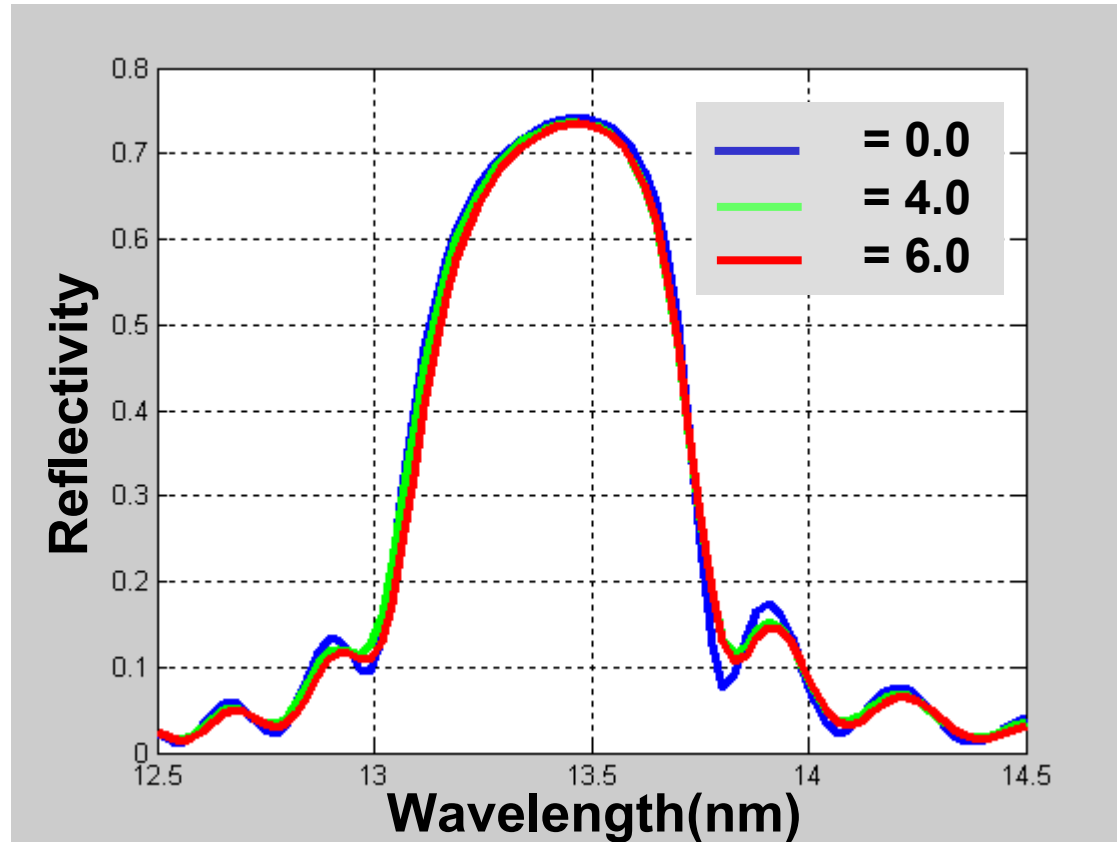
- Thickness of Mo/Si = 2.8 nm/4.1 nm.
- In annular illumination condition wavelength shift of maximum reflectivity is slightly greater than in the conventional one.

Reflectivity vs Wavelength for $t = 0, 4, 6$ with $NA = 0.3$ and $n = 1.0$ (Modified Thickness)



- Wavelength shift is adjusted by **tuning Mo/Si thickness** in conventional illumination condition.

Reflectivity vs Wavelength for $\theta = 0, 4, 6$ with NA = 0.3 and $\lambda = 0.5 \sim 1.0$ (Modified Thickness)



- Wavelength shift is adjusted by **tuning Mo/Si thickness** in annular illumination condition.
- The thickness of maximum reflectivity depends on not only tilt angle but also illumination condition.

Conclusions

- ❑ Expression for incident angle of beam coming from each position in illumination aperture is derived using coordinate transformation.
- ❑ Reflectivity start to decrease significantly around the tilt angle of 5° .
- ❑ Wavelength of maximum reflectivity shifts to the shorter wavelength side as θ increases.
- ❑ **Wavelength shift of reflectivity curve is adjusted by tuning Mo/Si thickness.**
- ❑ **The thickness of maximum reflectivity depends on not only tilt angle but also illumination conditions.**